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The Status of Measurement of the Mediterranean Mean Dynamic Topography by Geodetic Techniques

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Abstract

We review the measurement of the mean dynamic topography (MDT) of the Mediterranean using ellipsoidal heights of sea level at discrete tide gauge locations, and across the entire basin using satellite altimetry, subtracting estimates of the geoid obtained from recent models. This 'geodetic approach' to the determination of the MDT can be compared to the independent 'ocean approach' that involves the use of in situ oceanographic measurements and ocean modelling. We demonstrate that with modern geoid and ocean models there is an encouraging level of consistency between the two sets of MDTs. In addition, we show how important geodetic MDT information can be in judging between existing global ocean circulation models, and in providing insight for the development of new ones. The review makes clear the major limitations in Mediterranean data sets that prevent a more complete validation, including the need for improved geoid models of high spatial resolution and accuracy. Suggestions are made on how a greater amount of reliable geo-located tide gauge information can be obtained in the future.

1. Introduction

This paper discusses the mean dynamic topography (MDT) of the Mediterranean and its measurement by geodetic techniques. The MDT is the amount by which the Mean Sea Surface (MSS) is further from the centre of the Earth than a surface called the geoid, which is an equipotential surface resulting from the Earth's spatially-varying gravity field, and which would correspond to the MSS in the absence of an ocean circulation. An accurate measurement of the MDT can, therefore, provide oceanographers with insight into the circulation. Conversely, knowledge of the circulation, obtained by a number of oceanographic techniques can be used to infer the MDT.

Much is already known about the mean circulation of the Mediterranean and its variability (e.g. Pinardi and Masetti 2000) and, therefore, also about the spatial variation of its MDT. This insight has largely been obtained using in situ oceanographic measurements and ocean modelling. However, in recent years major advances have been made in geodetic techniques that have enabled the MDT to be determined, for the first time, as the difference between MSS and geoid to the accuracy required for oceanographic research (e.g. Bingham et al. 2014). These techniques have primarily involved satellite altimetry to provide the MSS over the open ocean and space gravity to provide the geoid, complemented at the coast with the use of tide gauges equipped with Global Positioning System (GPS) equipment (Woodworth et al. 2012). By studying the Mediterranean, particular lessons can be learned in the use of these techniques, notably by pointing to missing infrastructure and data limitations, which can also be relevant to discussion of the MDT in other data-sparse regions around the world.

Models of the MDT in the Mediterranean have already been made by previous authors in various ways (e.g. Rio et al. 2014a). Consequently, the present paper focuses on reviewing how an MDT model can be compared to those obtained using modern geodetic methods. In Section 2 we provide further background to the concepts of the various surfaces involved. This leads in Section 3 to an assessment of the extent of the necessary geodetic infrastructure in this region. The coverage of, and gaps in, the various networks are described.

The next topic, discussed in Section 4, concerns the determination of the MDT at the coast using Mean Sea Level (MSL) data from tide gauges equipped with GPS receivers and state-of-the art models of the geoid. We then progress in Section 5 to considering the Mediterranean MDT obtained using satellite altimeter data and recently-available geoid models. Section 6 presents a discussion of the importance of the MDT information from Sections 4 and 5 in deciding between existing global ocean circulation models, and thereby in contributing to the development of new ones. A forward look of possible data developments in the Mediterranean and elsewhere is presented in Section 7, while Section 8 presents our conclusions.

Altogether, our aim has been to recognise the important progress that has been made in understanding the MDT, and therefore the mean circulation, of the Mediterranean, which may eventually have major benefit to a range of oceanographic and climate research. However, our intention has also been to point to limitations in existing data sets in the region which limit our ability to validate fully the new MDT information, and which must be addressed by future geodetic network development.

2. General Descriptions of the Mediterranean Mean Sea Surface, Mean Dynamic Topography and Geoid

The last three decades have seen major technical developments that have revolutionised the measurement, and understanding, of spatial variations in the MSS. These include the use of the GPS at coastal tide gauges, which has enabled sea level measurements by a gauge to be expressed as heights relative to a reference ellipsoid. Over two decades of precise satellite radar altimeter data are also now available, with sea levels expressed in a geocentric reference frame and as ellipsoidal heights in a similar way to GPS-fixed tide gauge data. More recently, space gravity missions including the US-German Gravity Recovery and Climate Experiment (GRACE) and the Gravity Field and Steady-State Ocean Circulation (GOCE) mission of the European Space Agency have led to much improved models of the geoid.

The shape of the MSS is the same as that of the geoid plus the ocean MDT. In a world with no ocean circulation, the MSS and geoid would coincide. However, the ocean circulation provides an additional MDT component to the MSS varying spatially by between -2 and +1 metres at different points in the global ocean.

Figure 1 gives an overview of the MSS in the Mediterranean (measured relative to a reference ellipsoid). This shows the CLS2011 MSS (Schaeffer et al. 2012) that is available on a 2-minute grid from Archivage, Validation et Interprétation de données des Satellites Océanographiques (AVISO, www.aviso.altimetry.fr). The model makes use of data obtained over 1993-2009 from a number of altimeter satellites, with the resulting MSS referenced to the shorter period 1993-1999. The MSS varies from roughly 50 to 20 m west to east, with a low southeast of Crete at approximately 28°E, 34°N. This considerable spatial variation is due to the geoid component of the MSS, rather than the MDT which, it will be seen, has a spatial variation of only one or two decimetres. In particular, there are tight contours in the MSS (and geoid) around the low near Crete in the eastern Mediterranean, as will be referred to below.

Maps of the Mediterranean MDT have been derived by several authors using numerical ocean circulation models, some of which assimilate combinations of hydrographic (temperature and salinity), drifter and altimeter measurements (Dobricic 2005; Rio et al. 2007; Jordi and Wang 2009; Rio et al. 2014a). This is called the 'ocean approach' to the determination of the MDT (Higginson et al. 2015).

There are many similarities between these models. For example, that of Rio et al. (2014a) is called SMDT-MED-2014 and is representative of the period 1993-1999. It is provided on a 1/16° grid and has a formal error of approximately 6 mm in most parts of the Mediterranean (as demonstrated by a data set of MDT values and their errors provided by the authors). It is similar to that of Rio et al. (2007), also referenced to 1993-1999, but with a slightly reduced magnitude in its spatial variation. It shows the MDT falling along the European coast by approximately a decimetre between the Strait of Gibraltar and the south coast of France (Figure 2). It is largely flat until approximately 25° E in the Aegean and on the south coast of Turkey where it increases once again by 10 cm or more, retaining this higher value around the coasts of Lebanon, Israel and Egypt, reflecting the cyclonic circulation in the Levantine Sea (Poulain et al. 2012). Travelling east along the African coast, MDT retains its high value at the Strait of Gibraltar until the Egyptian and Israeli coast is reached. Overall, the MDT is consistent with existing knowledge of the Mediterranean circulation (Pinardi and Masetti 2000).

Figure 2 suggests that there should be a sea level gradient between southern Spain and North Africa. This suggestion is consistent with the known mean surface transport through the Strait of Gibraltar of approximately 1 Sv (10^6 m^3/sec) eastward and a slightly smaller return flow at depth westward, the difference being lost to strong evaporation over the Mediterranean (Criado-Aldeanueva et al. 2012). An assumption of an effective current thickness of 100 m in which the surface transport occurs (as inferred from Figure 8.4 of Farmer and Armi, 1988) implies from geostrophy a cross-Strait sea level difference of approximately 9 cm. The sea level fall from west to east through the Strait has been estimated using tide gauges and conventional levelling as approximately 15 cm (Levallois and Maillard 1970; Lisitzin 1974; Ross et al. 2000) and using a combination of observational and ocean modelling arguments as about 9 cm (Hughes et al. 2015).

The second method for determination of the MDT is called the 'geodetic approach' and involves subtracting a model of the geoid surface either from tide gauge MSL data expressed as ellipsoidal heights with the use of GPS, or from an altimetry-derived MSS model.

As explained above, the geoid in the Mediterranean will be similar to the MSS of Figure 1. However, for a determination of their difference (the MDT) it is necessary to derive a model of the geoid from combinations of satellite, terrestrial, marine and airborne gravity data, that is independent of the altimeter and tide gauge data that are used for the MSS model. As a result, the accurate determination of the MDT at short spatial scales depends on the accuracy of the geoid modelling at those scales, and in practice on the availability and quality of local terrestrial gravity information (e.g. Barzaghi et al. 2011). This is an important general issue for the Mediterranean, where the availability of terrestrial and marine gravity is more limited in the eastern Mediterranean and North Africa than in northern Europe (e.g. see the data holdings of the Bureau Gravimétrique International, http://bgi.omp.obs-mip.fr/), and is a particular issue for regions where the geoid changes rapidly from land to ocean. The coastlines of the eastern Mediterranean, including the south coast of Turkey, provide such example regions (Kiliçoğlu et al. 2011).

The GRACE and GOCE gravity missions have provided a major advance in knowledge of the geoid at medium wavelengths (typically 100-1000 km) with a succession of improvements in geoid models over the last few years (Pail 2013), and an accompanying increasing ability to separate MSS and geoid to determine the MDT. Most studies using these models have so far concentrated on Atlantic and Pacific coastlines, rather than the Mediterranean. However, the publication of the GOCE-only 'Release 5' models of the European Space Agency (ESA), the latest in this series of geoid models, provides an opportunity to perform an up-to-date Mediterranean assessment. For the present work, we have made most use of the 'Direct' version of these Release 5 models that we denote DIR5, which has been confirmed to represent the geoid signal without significant attenuation up to degree 220 by means of comparison of root-mean-square geoid differences at GPS/levelling points (Bruinsma et al. 2014; Gruber 2014; see also Gruber et al. 2011 for similar comparisons with earlier geoid models). We have also made use of a selection of earlier geoid models.

DIR5 is a satellite-only gravity field model constructed with LAGEOS 1/2, GRACE and GOCE data so as to provide high accuracy over a wide spectral range. ESA also provide a 'Time-wise' model (TIM5) based on GOCE information only, and so which we may expect to be less accurate at longer wavelengths, which we comment on below. For a discussion of the 'Direct', 'Time-wise' and 'Space-wise' methods, see Pail et al. (2011).

3. Overview of Existing Mediterranean Geodetic Infrastructure

The essential data requirement for the studies described in Section 4 is that an adequate amount of suitable sea level data must exist. In practice, given that the variability in MSL from year to year is of the order of a decimetre, several years of MSL information from a tide gauge would be adequate for our purposes to determine the time-averaged MDT to a few centimetres. The MSL values must be expressed relative to a benchmark on the nearby land. Information from many such sites can be obtained readily from the archive of the Permanent Service for Mean Sea Level (PSMSL, www.psmsl.org).

However, for these data to be useful for use in MDT studies, it is also necessary that the ellipsoidal heights of the benchmarks be known from GPS (Baker et al. 1997). GPS receivers are deployed permanently at many tide gauges around the world, with their data available from national or international data banks such as the Système d'Observation du Niveau des Eaux Littorales (SONEL, www.sonel.org). This mode of operation is called Continuous GPS (CGPS) and provides time series of vertical and horizontal movement of benchmarks within studies of long-term sea and land-level change

(Santamaría-Gómez et al. 2012). However, for present purposes it is only the time-averaged ellipsoidal heights of the benchmarks which concern us. Such heights can also be provided to adequate accuracy by means of 'epochal' or 'episodic' GPS (EGPS) deployments of receivers for perhaps several days or weeks (e.g. Becker et al. 2002). In both CGPS and EGPS, a fundamental requirement is that a local geodetic levelling connection, called a tie, has been made between the benchmark used for the GPS measurements and the reference datums of the gauges.

In earlier North American, European and Australian studies (e.g. Featherstone and Filmer 2012; Woodworth et al. 2012), it was possible to access the required tide gauge, GPS and local levelling information at a large number of sites. However, it will be seen that this is far from being the case for the Mediterranean. For the present study, we have extended the survey of European sea level infrastructure by Woodworth et al. (2009) in several respects, by considering the most recent status of the PSMSL datasets, and by supplementing the survey with information regarding the co-location of tide gauges with GPS. In brief, there are many tide gauges along the northern (European) coast of the Mediterranean, but many records are shorter than for Atlantic stations or have gaps, and few have been surveyed with either CGPS or EGPS. There are fewer suitable sites along the southern (African) coast. Figure 3 provides summaries of our new survey.

As of August 2014, there are 194 stations in the region represented in the PSMSL data set (Figure 3a). Of these, 66 tide gauges are indicated by SONEL as having a CGPS station nearby (Figure 3b), and 57 of those stations have some GPS observational data that are made available through SONEL (Figure 3c). This situation sounds encouraging. However, for our application, the number of useful GPS-equipped tide gauges reduces further to 21 stations as the necessary local geodetic ties have either not been made, or the levelling information has not been made available to SONEL (Figure 3d). The number of sites could be increased somewhat to 35 by also considering EGPS results, where available (blue squares in Figure 3d). Indeed, as mentioned above, an average ellipsoidal height is sufficient here. This can be achieved with a reasonable precision of 5 cm or better by carrying out a GPS campaign of several days (e.g. Becker et al. 2002). For CGPS stations within one kilometre of a tide gauge, we are confident that there is some hope of obtaining additional levelling tie information in the near future (9 of the stations shown by blue squares in Figure 3b).

Overall, the survey confirms the previous findings by Woodworth et al. (2009), that for North Africa there are far fewer tide gauges than for the European coast, and even less GPS information. As a matter of fact, the minimal infrastructure recommended for sea level and coastal land level applications in Europe and the Mediterranean some years ago (Figure 2 in Baker et al. 1997) remains elusive, in spite of several past efforts at initiating regional international coordination of sea and land level monitoring.

4. MDT Values at Mediterranean Tide Gauges

Knowledge of the MDT variation along the coast is of interest to oceanographers in studies of the coastal ocean circulation, and along some coastlines the MDT can change by many decimetres (e.g. Woodworth et al. 2012). The coastal MDT is also of interest to geodesists for which a long-standing objective has been the construction of a World Height System (WHS), which in effect means the use of a precise model of the geoid as a reference datum, replacing the many individual national datums based on MSL (Rummel 2012). Part of that work involves using coastal tide gauge data as a check of the consistency of variation of MSL along the coast with knowledge of the geoid and of the coastal MDT, the latter provided either by numerical ocean circulation models or by more general oceanographic insight. Such checks for the North American Pacific, Gulf of Mexico and Atlantic coastlines and the European

Atlantic coastline have been made by Higginson (2012), Woodworth et al. (2012), Higginson et al. (2015) and Lin et al. (2015). Similar studies for the Australian coastline have been made by Featherstone and Filmer (2012) and Filmer (2014). In those studies, the range of several decimetres in MDT along the different coastlines provided an opportunity to undertake the consistency checks of methods within different oceanographic regimes.

In this section, we extend such tide gauge studies to the Mediterranean. This region provides many contrasts to the North American and European Atlantic, in particular with regard to the unavailability of the amount of suitable data that we would like, as described in Section 3. This situation is most acute for the North African coast, with no stations available for inclusion in our study between Melilla in Spanish North Africa in the west and Alexandria in Egypt in the east.

Figure 4 shows the Mediterranean tide gauges for which a suitable amount of MSL information exists and where GPS surveys have enabled the MSL values to be expressed as ellipsoidal heights. These stations are also listed in Table 1. (Figures 3d and 4 have essentially the same information. A small number of the dots in Figure 3d represent more than one possible tide gauge/GPS combination. However, only combinations with adequate MSL data during 1993-2012 have been used in Figure 4 and Table 1.) In most cases, the GPS information was obtained from EGPS surveys during the past few years, with the details provided to us by tide gauge and GPS specialists in each country (Table 2). Several sets of EGPS information from short campaigns were already available through the European Union SEa Level Fluctuations (SELF) tide gauge benchmark projects in the Mediterranean (Becker et al. 2002). (Earlier discussion of SELF data can be found in Fenoglio (1996); Rhodos in Greece, which is included in Becker et al. (2002), could have been added to Table 1 but proved to be a significant outlier in our analysis.) In several cases, tide gauges were equipped with CGPS receivers and the relevant geodetic information is available from SONEL.

Analysis details followed closely those of Woodworth et al. (2012). Annual MSL values were obtained from the PSMSL and were adjusted for the inverse barometer (IB) effect using air pressure information from the National Centers for Environmental Prediction – National Center for Atmospheric Research (NCEP-NCAR) reanalyses (Kistler et al. 2001). Ellipsoidal heights were expressed in International Terrestrial Reference Frame (ITRF)-2005 or ITRF-2008, there being little difference in the heights expressed in the two frames (Altamimi et al. 2011). We standardised throughout on 'mean tide' coordinates for both MSL ellipsoidal heights and geoid values. A choice of tide system to use is not important as long as the same system is used for all GPS and geoid information.

One difference to Woodworth et al. (2012) is that we needed to make maximum use of the shorter records from the Mediterranean, with their data and gaps in different years. Table 1 shows that some of the records are very short. Therefore, we employed MSL information from a longer period of 1993-2012, which coincides with the period of available satellite altimeter data, making use of the fact that the interannual variability of Mediterranean MSL at most locations will have a spatial scale larger than the distance between a tide gauge and the nearest available altimeter data and the distance between altimeter ground tracks (e.g. Fenoglio-Marc 2001; Tsimplis et al. 2008; Calafat and Gomis 2009) . To each tide gauge annual MSL value a term A(*ref*) – A(*i*) was added, where A(*i*) is the annual mean sea surface height obtained from altimetry at the nearest point in the ocean to the gauge during year '*i*', while A(*ref*) is the mean sea surface height over the 'reference period' of 1993-2012. In this way, all the gauge data will be expressed as mean values representative of the reference period. Altimeter data were obtained from the 'reference' series of missions (TOPEX/Poseidon and the Jason series) in quarter-degree gridded form from AVISO (www.aviso.altimetry.fr/duacs/). These sea levels are provided with inverse barometer, tidal and all other instrumental and environmental corrections applied.

Geoid models employed included 'GOCO03S (Extended)', an older model used by Woodworth et al. (2012), wherein the GOCO03S model is based on satellite information only including data from the GRACE and GOCE space gravity missions (Mayer-Gürr et al. 2012). This is a development of GOCO02S and previous models by the Gravity Observation COmbination (GOCO, www.goco.eu, Pail et al. 2010). The 'Extended' refers to the use of GOCO03S to degree 180, to which information from the Earth Gravitational Model 2008 (EGM08) (Pavlis et al. 2012) has been added so as to provide a model to degree 2190. These model extensions were kindly performed for us by Dr. Thomas Gruber (Technical University of Munich) by simple combination of spherical harmonic coefficients for each model in each band. The use of the 'extended' models to degree 2190 is an attempt to represent the geoid at point positions, which will have omission uncertainties in present models, primarily due to the inadequacy of local gravity information. Of course, these uncertainties apply to many parts of the world coastline and not only to the Mediterranean.

We also made use of EGM08 itself (to degree 2190) and three more recent models. The 'TUM2013c (Extended)' model is an extension (again to degree 2190 using EGM08) of TUM2013c (Fecher et al. 2013). TUM2013c made use of more GOCE data than GOCO03S, as well as terrestrial gravity and gravity anomalies over the ocean inferred from satellite altimetry, and was complete to degree 720. GGMplus is a high-resolution geoid model resulting from a reanalysis of GRACE and GOCE satellite data, EGM08 and 'topographic gravity' worldwide, giving a model with a nominal spatial resolution of 250 m (Hirt et al. 2013). Finally, 'DIR5 (Extended)' comprises the Release 5 Direct model to degree 220, extended as before to degree 2190 using EGM08.

Figure 4 shows the height of the geoid above the ellipsoid for each model, relative to that for 'DIR5 Extended' at the same longitudes as the tide gauges above. Differences between models at locations in the western Mediterranean are of the order of 5 cm. A major exception is Ajaccio, on the west coast of Corsica, where there is a known steep geoid gradient. This is an important issue with regard to using the neighbouring ocean area for satellite altimeter calibration (Bonnefond et al. 2013). In this case, the 'DIR5 (Extended)' model differs from EGM08 by almost 30 cm and from 'TUM2013c (Extended)' by over 10 cm.

However, as one reaches approximately 26°E (approximately the middle of the Aegean and then the Turkish coast), model differences exceed 5 or even 10 cm for a number of stations and models, which implies an uncertainty in the geoid larger than any potential spatial variation in the MDT. This is almost certainly a consequence of greater shorter-scale variation in the geoid in this region, together with limited terrestrial gravity data. Overall, 'DIR5 (Extended)' compares equally as well to 'TUM2013c (Extended)', 'GOCO03S (Extended)' and GGMPlus (standard deviation of the differences of 58, 59 and 49 mm respectively) and less well for EGM08 (92 mm), largely because of the Ajaccio values.

An interesting demonstration of the geoid differences in similar models is given by comparing DIR5 to degree 200 (extended to 2190) to our reference model, DIR5 to degree 220 (extended to degree 2190), as shown in Figure 5 for the tide gauge locations. The differences between them have a standard deviation of 53 mm, similar to the values between 'DIR5 (Extended)' and other models in Figure 4. One notable difference is at the extreme western end of the Mediterranean, near the Strait of Gibraltar, where the degree 220 model has a geoid value larger than the degree 200 model for the first two stations and a small value for the next three, the differences being of the order of 10 cm, comparable to the larger differences obtained for the extreme eastern stations. The use of DIR5 to degree 220 rather than 200 appears to add useful information (see below).

MDT values obtained by differencing MSL ellipsoidal heights and geoid values from the 'DIR5 (Extended)' model are shown in Figure 6. Black circles refer to stations on the European coast, red open circles to stations on the North African or Israeli coasts, and solid blue circles to island stations. Between Gibraltar and 5°E, one can see a drop in MDT of approximately 20 cm, consistent with the ocean models described above. Between 5-26°E, MDT varies by typically ± 5 cm, which is an amount one might expect from previous knowledge of the MDT, added to which may be several-centimetre inaccuracy in geoid modelling in a region where models are largely consistent (Figure 4).

There is a slightly larger scatter of MDT values in the eastern Mediterranean, where Bodrum in Turkey and Alexandria in Egypt are the main outliers. However, this half of the Mediterranean demonstrates less scatter with 'DIR5 (Extended)' than with 'TUM2013c (Extended)' and other earlier models, although it is clearly difficult to arrive at a general conclusion as to model improvement with only a small number of stations for study. In practice, we know that the Turkish stations are well maintained with CGPS operated close to the gauges themselves, and so any residual scatter will be primarily a consequence of remaining geoid model inaccuracy. In the case of Alexandria, we suspect the accuracy of the MSL ellipsoidal heights, which were obtained from a local GPS survey relative to a CGPS station 3 km from the gauge.

The MDT values of Figure 6, derived using 'DIR5 (Extended)', correspond qualitatively to those of the Rio et al. (2014a) ocean MDT. The SMDT-MED-2014 model refers to the epoch 1993-1999. However, it can be made to correspond to 1993-2012 with the use of a corrector surface derived from the AVISO monthly mean sea level anomalies product on a grid with spatial resolution ¼°; this is the same altimeter data set as was used above. This correction amounts to ± 50 mm depending on location in the Mediterranean, with a median value of +14 mm. We denote this amended surface as RIO93-12 and its values at the tide gauge locations are shown by the dashed line in Figure 6. The SMDT-MED-2014 model is claimed to have a formal error from the mapping procedure of approximately 6 mm in most parts of the Mediterranean, although this will undoubtedly be smaller than the 'true' error (M-H. Rio, private communication). In addition, its accuracy will inevitably be lower after conversion to RIO93-12 with the corrector surface. Nevertheless, its error should be small enough such that the standard deviation of the differences between the two MDTs of 91 mm can be taken as one estimate of MDT accuracy using the 'geodetic approach' at point locations (tide gauges) in this region. This value is comparable to the accuracies of similarly measured MDT at American and European stations along the North Atlantic European coast (Woodworth et al. 2012; Hughes et al. 2015).

Similar comparisons with RIO93-12 using the 'TUM2013c (Extended)', 'GOCO03S (Extended), GGMPlus and EGM08 geoid models give standard deviations of 110, 116, 104 and 131 mm respectively. This suggests an encouraging greater level of agreement with the more recent 'DIR5 (Extended)' model, although the standard deviation values obtained in each case can be influenced by anomalous geoid values at particular locations as explained above.

The corresponding standard deviation with TIM5 (the GOCE-only geoid model) to degree 220 extended to 2190 with EGM08 is 87 mm, marginally better than for DIR5. DIR5 and TIM5 to degree 200 (extended to 2190) give 110 and 106 mm respectively, suggesting that there is more reliable information content in the degree 200-220 band in the new models. As shown above, this information plays a role in describing more reliably the MDT near the Strait.

Even though there has undoubtedly been major improvement in geoid models at medium wavelengths, primarily thanks to GRACE and GOCE (Pail 2013), comparisons between tide gauges and models remain dominated by several other factors. These include the accuracy of the time-averaged MSL measurement (which will be several cm for a short record, even with the altimetric corrections), accuracy in the GPS positioning and levelling (perhaps centimetric), and accuracy of the comparison MDT. An even more important factor will concern the accuracy of the geoid models at short wavelengths (which will be several cm, or even decimetric depending on location, as demonstrated to some extent by Figures 4 and 5). This accuracy will not have been improved by the recent space gravity missions and can be addressed only by more copious and accurate local gravity measurements.

5. MDT from Altimetry minus Geoid

In this section, we have compared the 'ocean' and 'geodetic' approaches to computation of the MDT using altimeter data for the entire basin instead of for tide gauges at point positions. The MDT from the 'ocean approach' is provided by the SMDT-MED-2014 model of Rio et al. (2014a) (Figure 2). This is then compared to MDT estimates from the 'geodetic approach', wherein a selected set of geoid models are subtracted from the CLS2011 MSS of Figure 1. The geoid models considered, described in Section 3, were 'DIR5 (Extended)', EGM08 and one of the earlier models, called 'GOCO03S (Extended)', that was used by Woodworth et al. (2012). Each geoid model has been computed on the same 1/16° grid as the Rio et al. (2014a) MDT, in the mean-tide system and referred to the TOPEX ellipsoid, for consistency with the altimetric MSS information. The CLS2011 MSS, with a spatial resolution of 2 minutes, was also interpolated onto the same grid. Both the CLS2011 MSS and SMDT-MED-2014 model are referenced to 1993-1999 so no corrector surface is needed in this case.

The resulting Rio et al. (2014a) MDT minus (MSS-geoid) differences using the three geoid models are mapped in Figure 7. Overall, the MDT between the two methods differs within approximately 5 cm of the mean-difference for most of the Mediterranean and for all three geoid models, although the older 'GOCO03S (Extended)' model has a slightly tighter distribution (Figure 7, bottom). There are significant differences evident in the spatial patterns. Long wavelength differences are larger when EGM08 is used, with maxima of as much as ~90 cm along the Adriatic and western Aegean coasts. It is notable that the new geoid model 'DIR5 (Extended)' presents structures similar to the older 'GOCO03S (Extended)', with even stronger patterns. In the western basin large differences for both models are found around Corsica, where negative values in excess of 20 cm can be observed. In the Eastern Mediterranean, the larger differences evident using the older models in coastal areas (where the MDT is itself higher, Figure 2) persist using the new model, with highest values in the Aegean and along the Levantine coast. Some of the spatial features are common in all three maps, such as the negative differences south of Crete, and higher values in the Aegean and north of Cyprus, which might be a consequence of errors in the Rio et al. (2014a) MDT field as well as errors common to all geoid models.

The individual fields used for Figure 7 have been resampled at 1/16° but they have different original spatial resolutions (1/16° for Rio et al., 2 minutes for CLS2011 and 0.16° for the geoid models). Therefore, their combination could introduce high-frequency noise into the mapping. Additional smoothing results in the distributions of Figure 7 (bottom) having smaller widths, but with central values the same to within 1 cm, and the most apparent features in the maps unchanged. For example, the red dashed line in Figure 7 (bottom) shows the corresponding distribution for the 'DIR5 (Extended)' model after the application of a Gaussian filter (75 km radius at half maximum). If one approximates the unfiltered and filtered 'DIR5 (Extended)' distributions in terms of Gaussian parameterisations (although note that the real distributions have much longer tails than for a Gaussian), then standard deviations of 6.0 and 3.8 cm respectively are obtained, or a factor of 2 reduction in variance in MDT difference.

MSS models will differ if other reference periods are used due to the variability of the ocean circulation (e.g. Jordi and Wang 2009). They will also differ if a different mix of satellites is employed, or, especially near the coast, if different algorithms are used for instrumental and tidal corrections and for merger of data from the separate missions. As an alternative MSS to CLS2011, we made use of the Technical University of Denmark (DTU) DTU10 global MSS model with a 1-minute resolution corresponding to a 17-year reference period 1993-2009 (www.space.dtu.dk). This model is a development of earlier MSS models by Andersen and Knudsen (2009), and is also constructed from data from a number of satellites. This MSS surface was interpolated onto the same 1/16° grid, and a corrector surface computed so as to provide a MSS referenced to 1993-2012. The median correction for the basin is only +4 mm due to the reference epochs 1993-2009 and 1993-2012 being similar. (We also considered making use of the recently available DTU13 MSS which is constructed from data from more altimeter missions than DTU10 and is referenced to 1993-2012. However, this model displays more spatial differences to DTU10, particularly in coastal areas, than one might have expected from only a small number of additional years, and we were advised by Dr. Ole Andersen to continue instead with our approach of using DTU10 and a corrector surface.)

The corrected DTU10 MSS, after geoid subtraction, gives an MDT that can be compared to the RIO93-12 ocean MDT. We made use once again of the three geoid models of Figure 7. In each case, the DTU10 MDT compared to the RIO93-12 ocean MDT presented a similar spatial pattern as for the CLS2011 MDT compared to SMDT-MED-2014 in Figure 7, although with the differences shifted to more negative values. On average, the differences for DTU10 peaked at around -6 cm rather than approximately -4 cm for CLS2011 in Figure 7 (bottom).

This ~2 cm shift was confirmed to be largely a consequence of the median-difference between the two MSS products. When both MSS models were adjusted to the 1993-2012 reference period with the use of corrector surfaces, differences between them were found to be typically 5 cm or less for most parts of the Mediterranean (Figure 8), with a median-difference of 2.4 cm (3.2 cm for the uncorrected surfaces), and with DTU10 being on average slightly above the CLS2011.

One reason considered for the shift is that MSS products are derived from along-track altimeter data with an inverse barometer (IB) correction. For the first years of the TOPEX/Poseidon mission and for the early MSS models of Andersen and Knudsen (2009), a reference air pressure of 1013.3 mbar was used. That was subsequently replaced in altimeter processing by a Dynamic Atmosphere Correction (DAC) for higher-frequency air pressure affects and an IB correction for lower frequencies that used the mean surface air pressure over the global ocean as its reference. That global mean would have been approximately 1011 mbar when averaged over several years, which would have led to a bias between older and newer MSS models of approximately 2 cm. However, both CLS2011 and DTU10 MSSs used the later DAC+IB method. Consequently, this aspect cannot explain the median difference of approximately 2 cm between them.

Non-zero mean values can also enter in the 'geodetic approach' through the way geoid surfaces are computed, depending on whether or not analysts have followed the same procedures for reference gravity potential (see discussion in Section 4.4.3 of the GOCE Data Handbook, ESA 2010). All the geoid values computed in the present report were computed at the Technical University of Munich, and the same procedures were followed, so any computational biases will be common to all model values. One could, furthermore, imagine offsets occurring in the 'ocean approach' related to the effective choice of reference surfaces in the ocean ('levels of no motion') when using drifters and hydrography.

Overall, the mean-differences in Figure 7 aside, we conclude that the differences between the two methodologies to estimate MDT in the Mediterranean Sea have a standard deviation of the order of 5 cm, and even larger in some areas, which corresponds to a large fraction of the MDT signal itself, and is similar to our experience using tide gauge data in Section 4. Some of the spread in Figure 7 (bottom) will stem from errors in the geoid models as demonstrated by the differences between the three maps. However, given the several cm differences between CLS2011 and DTU10 MSS models shown in Figure 8 (let alone the differences between DTU10 and DTU13 alluded to above), one cannot assign all of the differences between the Rio et al. and geodetic MDTs in Figure 7 to geoid error alone.

Figure 9(a) shows the MDT within the basin computed using the 'DIR5 (Extended)' geoid (i.e. DIR5 to degree 220 extended to 2190), which represents our present best estimate of Mediterranean MDT using the 'geodetic approach'. This is similar to that of Rio et al. (Figure 2) but reflects the spatial noise still to be found in an MDT obtained using this approach. (Almost the same map is obtained using DIR5 to degree 200 extended to 2190, although with localised changes in the spatial noise.) Figure 9(a) also shows the MDT values at tide gauges, corresponding to those in Figure 6 and Table 1, but adjusted so that their average is the same as that obtained from the closest grid points of the altimeter-derived geodetic MDT. As concluded from Figure 6, when comparing the tide gauge MDT values to those of Rio et al. (2014a), the spatial variations along the coast in the two sets of geodetic MDT values can be seen to be consistent at most of the tide gauge sites considered. However, there exist some stations with large discrepancies. This is the case of the southern Spanish coast in the Alboran basin with the stations of Malaga and Almeria. Ajaccio in Corsica is also an outlier, but this may be related to the large uncertainty of the altimeter-derived MDT in this area (see differences between 'geodetic' and 'ocean' approaches in Figure 7). Several sites in the eastern Mediterranean display coastal MDT significantly different from their surroundings. Figure 9(a) also demonstrates the much higher MDT of the Black Sea than the Mediterranean (by ~30 cm), as has been known for many years from conventional geodetic techniques (Lisitzin 1974).

The spatial noise in the MDT can stem from several sources. For the geoid model, DIR5 has an estimated accuracy of 1.7 cm around 100 km half-wavelength (degree 200) (Bruinsma et al. 2014). However, in order to obtain the higher spatial resolution for 'DIR5 (Extended)', we have relied on the addition of coefficients from EGM08 to degree 2190. To be truly consistent, this combination should be undertaken in a joint GOCE-altimetry solution, rather than via simple combination of two different models, which will be a source of noise. In addition, the EGM08 coefficients will have been determined partly by altimeter gravity anomalies over the ocean (Pavlis et al. 2012), and hence will represent some aspects of the MDT itself which introduces a further source of noise. For the MSS component, one depends on interpolation of data from multiple missions with different ground tracks and duration which will lead to (largely unknown) spatial variations in MSS error. Several sophisticated approaches to optimal filtering of an altimetric MDT have recently been developed (e.g. Bingham et al. 2011; Knudsen et al. 2011; Slobbe et al. 2012; Becker et al. 2014), each of which has pointed to the deficiencies of simple low-pass spatial filtering of the MDT field to reduce noise. However, in the present case we believe that such a simple approach is adequate in describing the MDT's main features. Figure 9(b) shows the same MDT information as for Figure 9(a) after the application of a Gaussian filter (75 km radius at half maximum). The filter kernel at each point is determined by the pattern of ocean gridpoints present, so that it becomes a one-sided Gaussian close to the coast, rather than an isotropic filter.

The MDTs of Figures 9(a) and (b) are similar to that of Rio et al. (2014a) (Figure 2), with generally larger values in the south of the basin and smaller ones in the north, but higher coastal values in the south-central part of the Mediterranean north of Libya rather than along the Algerian coast. These findings have been confirmed by a separate computation of the MDT for 1993-2012 using the DTU10 MSS together with the TUM2013c geoid (to degree 720), further filtered with a 75 km Gaussian filter (Figure 9c). TUM2013c employs DTU10 altimetric gravity anomalies, so this improves the consistency of the solution, significantly reducing the noise on shorter length scales than those shown here. The similarity of MDTs in Figures 9(a-c) is encouraging. A further confirmation of the main features of our MDT spatial patterns in Figure 9 comes from the study of Gilardoni et al. (2014) who employed a Wiener filter approach (using a priori knowledge of MDT spatial covariances from external sources) applied to the CLS2011 MSS together with the TIM5 geoid.

6. Discussion of the Importance of Independent MDTs to Global Ocean Modelling

We can demonstrate how important it is to have information on the MDT of the Mediterranean, from both oceanographic and geodetic sources, in deciding between existing global ocean circulation models, and thereby in contributing to the development of new ones. The Mediterranean exchanges water with the Atlantic Ocean through the Strait of Gibraltar, with about 1 Sv upper-layer flow into the Mediterranean, most of which returns to the Atlantic in a lower layer, apart from a small amount of water which is lost to evaporation. However, the hydraulic controls through the Strait are complicated (Farmer and Armi 1988), and are represented differently in different global ocean models (some models have no exchange at all).

Different models provide different profiles of MDT around the Mediterranean coastline. Figure 10 shows a subset of profiles discussed by Hughes et al. (2015), for models that have a reasonably-sized exchange flow with the Mediterranean (between 0.5 and 1.6 Sv). There are seven of them, identified by the names and colours shown, and they are relevant for the epoch 1996-2000. They are plotted as a function of distance anti-clockwise from the Strait, with their overall levels adjusted to have the same MDT along the adjacent Atlantic coast between 30-35° N, for reasons that are discussed in detail by Hughes et al. (2015). To help the reader align the profiles to the Mediterranean coastline, the 1000 km intervals shown on the abscissa of Figure 10 can be located in Figure 1.

Each profile can be seen to be generally negative. However, they differ considerably in detail, notably for the Occ12 model in the Aegean. We will not discuss these differences here. Our point is simply to show that they exist in the different models at the decimetre level. Also shown in dark blue is a 1996-2000 average MDT that is made available by AVISO and called Duacs-2014 (V15.0). That MDT is based on the AVISO reprocessing of gridded satellite altimetry data and incorporates some earlier geoid information from GOCE, so it will differ slightly in its geoid content from the MDTs discussed in Sections 4 and 5.

The dots in Figure 10 show values of MDT obtained from the tide gauges using the 'DIR5 (Extended)' geoid model. Black dots indicate MDTs relevant to 1996-2000 (but making use of data from 1993-2012, see Hughes et al. 2015), whereas the red dots are relevant to 1993-2012 as used in Section 4. There are only small differences between the black and red dots, so any differences are not important to the present discussion. Their overall level in the figure is determined by alignment to the average of the profile of the Duacs-2014 (V15.0) MDT and those of the two Nemo ocean models, again as discussed by Hughes et al. (2015).

In addition, Figure 10 shows (in black) the MDT profile from Rio et al. (2014a). That model, as explained above, applies to 1993-1999 but has been adjusted to 1996-2000 using an altimetric corrector surface. The tide gauge MDT values support those of Rio et al. (2014a) within their large scatter but they lie systematically below the profiles of many of the models. The acquisition of data from the North African section of the coast can be seen to be particularly important for model verification.

Consequently, our point in providing these model comparisons is simply to show how more (and ideally more precise) tide gauge MDT information from around the coastline could be used to judge between different model schemes. More information would represent an important contribution to global ocean circulation modelling in general, not only for the Mediterranean. This naturally leads on to a discussion in the next Section of methods of enhancing the regional geodetic data sets.

7. Discussion concerning Future Geodetic Data from the Mediterranean

Although some progress has been made in providing the Mediterranean region with modern tide gauges and GPS receivers, much more investment in infrastructure is needed. Figure 3 demonstrated that major gaps occur between tide gauge stations along some parts of the European coast, while the North African coast has only three useful stations. Where CGPS is operated near to gauges, in many cases either the necessary geodetic ties have not been made or the information is not readily available. Sometimes data are available from EGPS surveys together with levelling information. However, in these cases the information often takes the form of ellipsoidal heights computed by local agencies using different software and data spans (information that has usually not been provided to us). In the case of one country represented in Tables 1 and 2, the EGPS ellipsoidal heights had to be purchased as they are not routinely made available freely to the international sea level community.

It is clear that more CGPS receivers, and levelling ties, are needed at Mediterranean tide gauges. The Global Sea Level Observing System (GLOSS) programme of the Intergovernmental Oceanographic Commission of UNESCO calls in its implementation plan (IOC 2012) for the upgrade with CGPS receivers at its core network of tide gauge stations. It further calls for their observations and metadata to be provided to its dedicated data assembly centre (namely SONEL at the University of La Rochelle), so that the observations and generated products can be provided freely in accordance with IOC/UNESCO oceanographic data exchange policy. In the same spirit, CGPS upgrades should be considered at many sites in the Mediterranean.

However, a second-best option would be for agencies to make EGPS data (and levelling information) available to a centre such as SONEL. If the raw data are available, then web-based tools, such as the Canadian Spatial Reference System Precise Point Positioning (CSRS-PPP) from National Resources Canada can be used to process them (http://www.nrcan.gc.ca/earth-sciences/geomatics/geodetic-reference-systems/tools-applications/10925#ppp). These tools are freely available and can provide any agency with high-performance GPS positioning within a state-of-the-art processing strategy. Consequently, if the agency prefers, the data can be processed locally, and results passed to SONEL, instead of providing SONEL with the data itself. Typically, campaign-based EGPS observations of several days' duration can be processed in less than a day, with a resulting precision of ellipsoidal heights better than 5 cm. As part of the present study, we have tested the above-mentioned web tools and have confirmed that heights can be computed that differ by only 2-3 cm from those obtained using the latest solutions from SONEL (Santamaría-Gómez et al. 2012).

Consequently, in the context of the present study, we believe that EGPS campaigns spanning a few days can become a worthwhile alternative to CGPS to supplement the existing data gap coverage of tide gauges with ellipsoidal information (Figure 3). In addition, reprocessing of past EGPS observations, now hopefully safely archived at geodetic centres, would be very worthwhile, provided the essential metadata are accessible (e.g. antenna type, which is a critical issue in knowing how to process the data).

Further important metadata aspects, which sound straightforward but which nevertheless need to be improved in existing data sets (Mediterranean and global), concern the need to know the exact positions of tide gauges and CGPS/EGPS measurements and the methods used for the levelling ties. The PSMSL data set, for example, has given historically the positions of tide gauges to one minute, although the modern data set does now allow for storing locations to higher precision. Until the era of GPS and modern geodesy, one minute precision was adequate, and in fact would still be adequate for present purposes if the stated locations were always correct. However, in some circumstances, lack of documentation on gauge location in a large port, and sometimes on changes within the port, has meant that location accuracy will have been worse than one minute (the PSMSL web site provides a clear warning on this topic). This inaccuracy will manifest itself in a slightly incorrect estimate of the geoid at the gauge in an analysis such as Section 4.

Another issue concerns the method used for the ties between CGPS/EGPS benchmark (GPSBM) and the Tide Gauge Benchmark (TGBM), in order to express the MSL data as ellipsoidal heights. If differential GPS is used for the tie, then the GPSBM and TGBM will be both automatically in the form of ellipsoidal heights as required. However, if a levelling connection is made between GPS station and tide gauge, as recommended by IOC (2006), and if they are some distance apart, one has to consider the geoid-difference between them. This factor has been ignored in most studies, such as that of Section 4, wherein it is assumed (no doubt correctly in most cases) that the two are nearby. Otherwise, the correct procedure would be to employ the ellipsoidal height of the TGBM as calculated previously, together with a geoid value at the GPS station, rather than at the gauge. One notes that the geoid difference could well be several cm, or even decimetric, over several km. In future studies it will be necessary to improve as far as possible all such relevant metadata information in data banks such as PSMSL and SONEL.

8. Conclusions

The discussion of data availability in the Mediterranean could undoubtedly be repeated for other regions with similar sparse coverage. However, Sections 4-6 have shown that such modest amounts of tide gauge information, complemented by satellite altimeter data, can be used in the 'geodetic approach' to validate models of the MDT obtained by the 'ocean approach' which involves the use of independent in situ oceanographic information and ocean models.

The tide gauge study of Section 4 has involved the use of data from a limited number of stations, with few of them covering the complete reference period of 1993-2012. In addition, their MSL values have been expressed as ellipsoidal heights with the use of a mixture of CGPS and EGPS information, the latter derived from different agencies using different software to express heights in different geodetic reference frames, requiring translation into the consistent frame that we need (i.e. ITRF-2005 or -2008). In spite of this sparse and inhomogeneous data set, comparison of its derived MDT values to those of the ‘ocean approach’ (the Rio et al. (2014a) MDT in this case) indicates a comparable accuracy to MDT values obtained along Atlantic, Pacific and Australian coastlines where more copious amounts of data are available.

It has been asked why one should care about the coastal MDT obtained by tide gauges at all, given the progress that has been made in employing satellite altimetry for MDT determination throughout the ocean basins (as discussed in Section 5). However, the coastal oceans in many parts of the world (approximately 100 or 200 km from the coast) contain strong MDT signals. These signals are not represented well by the presently available altimetric MSS products that are highly inaccurate when interpolated and extrapolated near the coast, especially for a complicated coastline such as the Mediterranean. Although the development of more precise coastal altimetry is making progress (Vignudelli et al. 2011), tide gauges currently provide the only means of obtaining reliable coastal MDT information. Unfortunately, much of the narrow coastal MDT signals in the Mediterranean occur along the North African section of the coast (Figure 2) for which there are little data (Figure 3). One aim of our review has been to point to that deficiency.

Satellite altimetry, together with a geoid model, provides a means to compare an MDT from the ‘geodetic approach’ with that of the ‘ocean approach’ MDT of Rio et al. (2014a) throughout the Mediterranean. Although it is true that altimetry was employed in the construction of the Rio et al. (2014a) model for removal of temporal variability from drifter velocities, that model was based primarily on drifter and hydrographic data sets. Therefore, it can be considered as an ‘ocean MDT’, independent of the geodetic (altimetry together with geoid) MDTs that we have investigated. Our estimates of MDT using the CLS2011 MSS, together with three different geoid models, differ spatially from those of Rio et al. by typically ± 5 cm (Figure 7, similar findings apart from an offset having been obtained using the alternative DTU10 MSS). This provides, as far as possible, an independent assessment of the accuracy of a published ocean MDT model. Although our geodetic MDTs (Figures 9a-c) are largely consistent with that of Rio et al., with generally larger values in the south of the basin and smaller ones in the north, one difference is off the coast of Libya where higher values are suggested than along the Algerian coast. Further insight into the true MDT will be obtained from analysis of geodetic and ocean MDTs in combination, with careful attention to their relative errors and with the use of optimal filtering to ensure compatibility as performed by Rio et al. (2014b) for the main ocean basins.

The tide gauge and altimeter studies both indicate the progress that has been made in geoid model development, largely thanks to the availability of data from the GRACE and GOCE gravity missions, and the discussion of Section 6 has shown how important these developments are to modelling and understanding the regional and global ocean circulation. Nevertheless, it is the case that further refinement of geoid models is required for more accurate MDT determination at tide gauges, using more copious terrestrial, marine and airborne gravity for geoid determination beyond approximately degree 220. This is a particular requirement for regions of steep geoid gradient, such as the coastline of Turkey, and where there is a need to use pairs of tide gauges for accurate determination of sea-surface slopes, the Strait of Gibraltar being an obvious example.

We hope that the present review has demonstrated the synergies between oceanography and geodesy that can lead to greater insight into the ocean circulation. As a result, we hope to have encouraged further investment in the geodetic networks and data sets that the Mediterranean requires for future research.

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Figure Captions

1. The mean sea surface (relative to a reference ellipsoid) in the Mediterranean using the CLS2011 model. This model makes use of data obtained over 1993-2009 from a number of altimeter satellites, with the resulting MSS referenced to the shorter period 1993-1999. The numbers along the coastline indicate the intervals of 1000 km presented in Figure 10.

2. The SMDT-MED-2014 model of the Mediterranean MDT from Rio et al. (2014a). The model is referenced to the period 1993-1999. Its spatial average formal uncertainty is approximately 6 mm.

3. Existing tide gauges in the Mediterranean for which data are publicly available:
(a) with MSL data available at PSMSL in either its Revised Local Reference or Metric subsets;
(b) subset of (a) with a CGPS station nearby;
(c) subset of (b) with GPS measurements available at SONEL;
(d) subset of (a) with GPS data from either CGPS stations (equivalent to (c)) or EGPS campaigns, but with geodetic ties available in either case.

4. (top) Locations of tide gauges with data available for this study. (bottom) Height of the geoid from the 'TUM2013c (Extended)', EGM08, 'GOCO03S (Extended)' and GGMplus models, relative to that of the 'DIR5 (Extended)' model at the above locations.

5. Differences between two 'DIR5 (Extended)' models for which the DIR5 components are to degree 200 or 220, both being extended to degree 2190 using EGM08.

6. The MDT for the reference period 1993-2012 observed at the tide gauges in Figure 4. Black circles refer to stations on the European coast, red open circles to stations on the North African or Israeli coasts, and solid blue circles to island stations. The dashed line connects values of the RIO93-12 MDT model (derived from that of Rio et al. 2014a) at each location, with an offset such that the average MDT values using the 'geodetic' and 'ocean approaches' are the same.

7. The SMDT-MED-2014 ocean MDT model of Rio et al. (2014a) minus the MDT computed as a difference between the CLS2011 MSS and a recent geoid model: (top) 'DIR5 (Extended), (middle) EGM08 and (bottom) 'GOCO03S (Extended)'. The lower figure contains histograms of differences across the basin for each geoid model. The red dashed curve shows the distribution for 'DIR5 (Extended)' after the additional filtering described in the text.

8. Differences between the DTU10 and CLS2011 MSS models in the Mediterranean, both models adjusted using corrector surfaces to reference them to 1993-2012 as described in the text.

9. (a) MDT for the Mediterranean Sea using the CLS2011 MSS (adjusted to 1993-2012) and the 'DIR5 (Extended)' geoid model. The dots along the coast show MDT values for the tide gauges in Table 1 and Figure 6 adjusted to correspond to the MDT values from MSS minus geoid, as described in the text. (b) As for (a) with the application of a 75 km (radius at half maximum) Gaussian filter. (c) The corresponding MDT using the DTU10 MSS and TUM2013c geoid model and a 75 km Gaussian filter.

10. Profiles of MDT around the Mediterranean, anti-clockwise from the Strait of Gibraltar, for seven global ocean circulation models with names as shown, all relevant to epoch 1996-2000 (for details and full references, see Hughes et al. 2015). The Duacs-2014 (V15.0) MDT, also for 1996-2000, is shown in

dark blue, while that of Rio et al. (2014a) adjusted to 1996-2000 with the use of an altimetric corrector surface, is in black. MDT values from tide gauges, using the 'DIR5 (Extended)' geoid model, are shown by the black and red dots for epochs 1996-2000 and 1993-2012 respectively. To align distances with points on the coastline, see the distance markers every 1000 km in Figure 1.

Table 1. Tide gauge stations used for the determination of MDT showing PSMSL combined coastline and station code, station name, longitude and latitude, number of years of MSL data available between 1993-2012 (*), and MDT in millimetres using the 'DIR5 (Extended)' geoid model.

The final column shows the source of GPS ellipsoidal heights and levelling information at each site using the codes of Table 2. 'B' refers to EGPS information published by Becker et al. (2002), while 'LR' refers to either CGPS or EGPS information provided by SONEL.

220024	Tarifa	-5.603	36.007	3	195.340	E
215001	Gibraltar	-5.350	36.133	5	249.988	G
220031	Malaga	-4.417	36.717	20	358.250	E
220044	Almeria	-2.478	36.830	7	361.332	E
220051	Alicante	-0.483	38.333	3	153.871	E
220056	Valencia	-0.333	39.467	17	138.887	E
225011	Mallorca	2.633	39.550	11	259.270	E
225021	Ibiza	1.450	38.917	9	114.898	E
230021	Sete	3.699	43.398	12	170.258	LR
230051	Marseille	5.350	43.300	14	65.352	LR
232001	Ajaccio	8.763	41.923	7	24.223	LR
250011	Genova	8.900	44.400	1	155.605	B
270037	Porto Garibaldi	12.249	44.678	3	217.754	LR
270054	Venice	12.333	45.433	8	106.637	B
270061	Trieste	13.759	45.647	20	78.746	B
279002	Koper	13.750	45.567	10	25.504	LR
280031	Split	16.442	43.507	19	97.574	C
290065	Alexandroupolis	25.878	40.844	18	143.199	B
290101	Iraklion	25.153	35.348	9	215.578	B
290021	Kalamai	22.116	37.024	16	134.486	B
290017	Katakolon	21.320	37.645	16	94.238	B
290001	Preveza	20.757	38.959	17	205.932	B
290081	Siros	24.946	37.440	16	118.836	B
310042	Mentes	26.717	38.433	10	122.199	T
310046	Bodrum	27.417	37.033	12	-25.344	T
310052	Antalya	30.617	36.833	12	158.133	T
310066	Iskenderun	36.181	36.594	5	145.232	T
310071	Erdemli	34.250	36.567	6	230.156	T
320016	Hadera	34.883	32.467	15	-44.439	I
330071	Alexandria	29.917	31.217	14	79.310	E
340003	Melilla	-2.928	35.291	5	263.879	S
340001	Ceuta	-5.317	35.900	19	296.180	S

(*) No MSL data were available for Koper for 1993-2012, so data for the earlier complete decade 1982-1991 were employed so as to take advantage of that station having GPS measurements and geodetic ties. IB corrections were made as for other sites but no altimeter correction was possible for the earlier period. Instead, an ad hoc adjustment of 35 mm was applied derived by comparing IB-corrected Trieste MSL data for 1982-1991 to that for 1993-2012.

Table 2. Tide gauge and GPS specialists who provided information on the ellipsoidal heights of tide gauge benchmarks based on EGPS measurements. See also Table 1.

Source Code	Stations	Contact Person
C	Split	Hrvoje Mihanović, Hydrographic Institute, Croatia
E	Alexandria	Cécile Shaalan, Centre d'Études Alexandrines, Egypt
G	Gibraltar	Richard Bingley, University of Nottingham, UK
I	Hadera	Dov Rosen, Israel Oceanographic and Limnological Research Institute
S	All Spanish coast and Spanish North Africa stations	Pedro Gonzalo López and Bernat Puyol Montserrat, Instituto Geográfico Nacional, Spain
T	All Turkish stations	Hasan Yildiz, General Mapping Command, Turkey

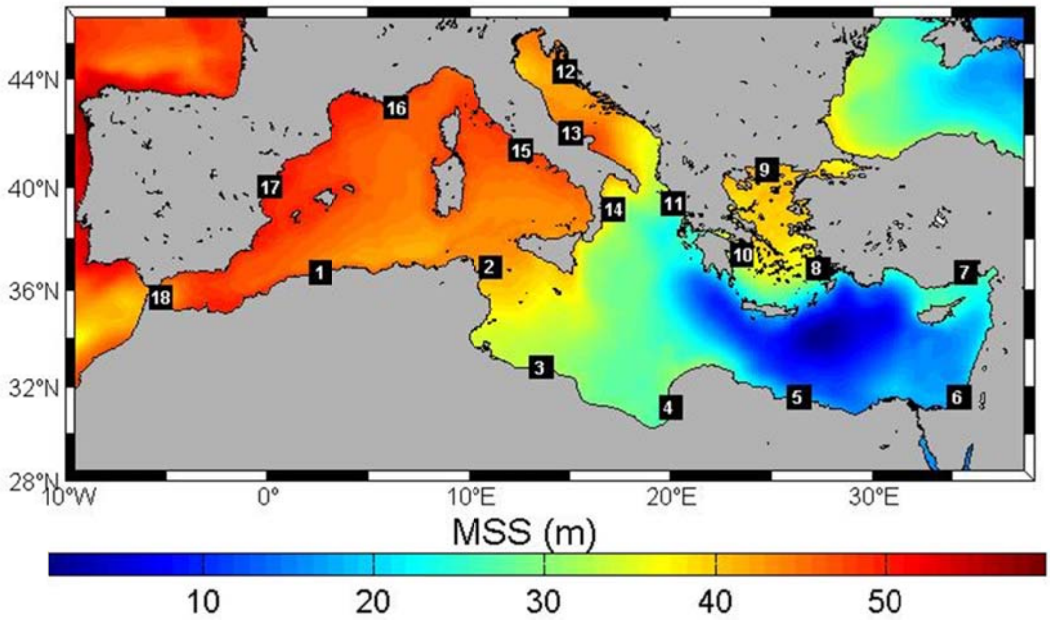


Figure 1

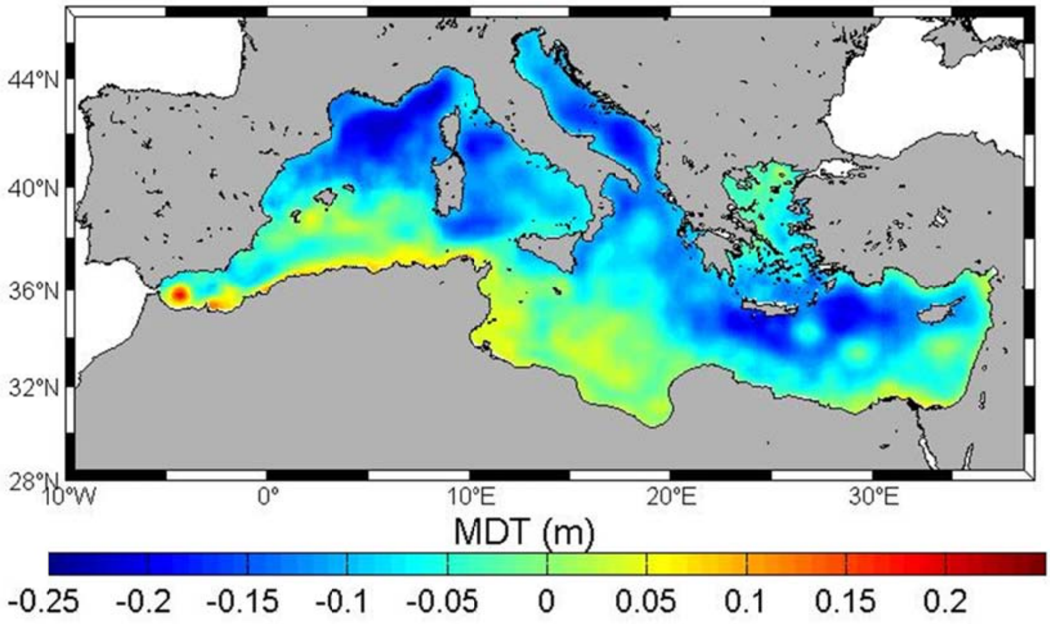


Figure 2

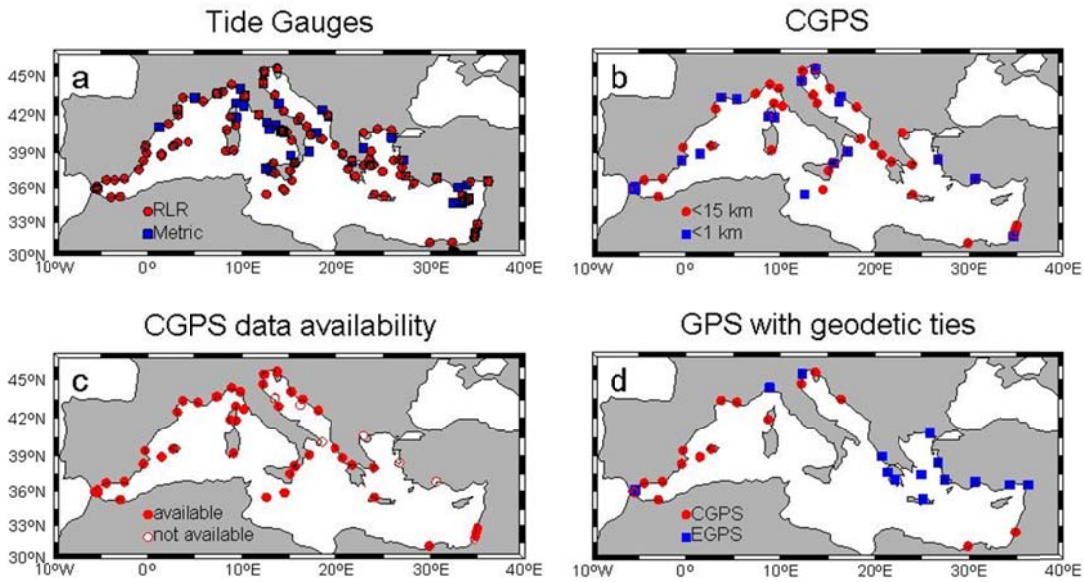
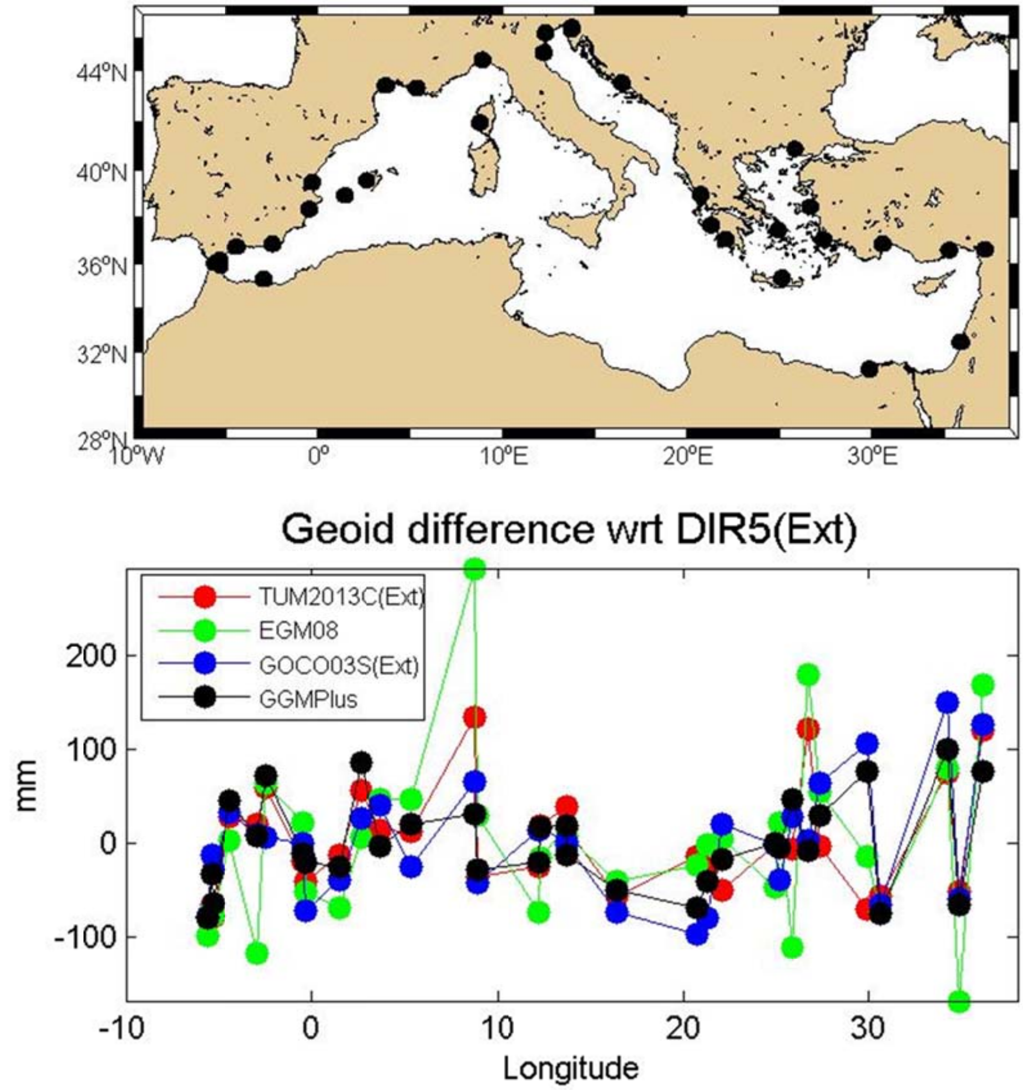

Tide Gauges
CGPS
CGPS data availability
GPS with geodetic ties
a
b
c
d
RLR
Metric
<15 km
<1 km
available
not available
CGPS
EGPS
45ºN
42ºN
39ºN
36ºN
33ºN
30ºN
10ºW
0º
10ºE
20ºE
30ºE
40ºE

Figure 3



44ºN
40ºN
36ºN
32ºN
28ºN
10ºW
0º
10ºE
20ºE
30ºE
Geoid difference wrt DIR5(Ext)
TUM2013C(Ext)
EGM08
GOCO03S(Ext)
GGMPlus
mm
200
100
0
-100
-10
0
10
20
30
Longitude

Figure 4

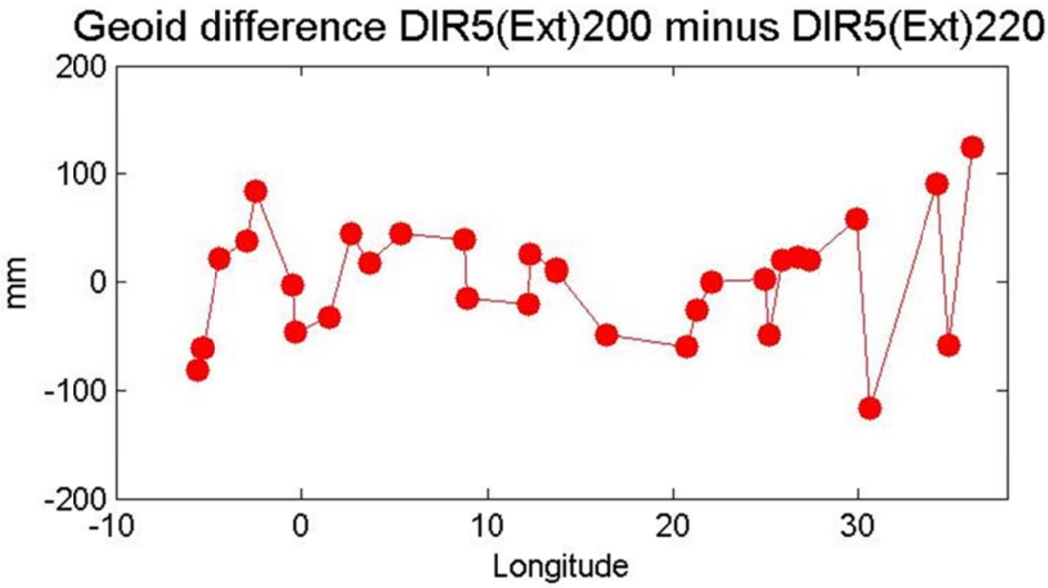


Figure 5

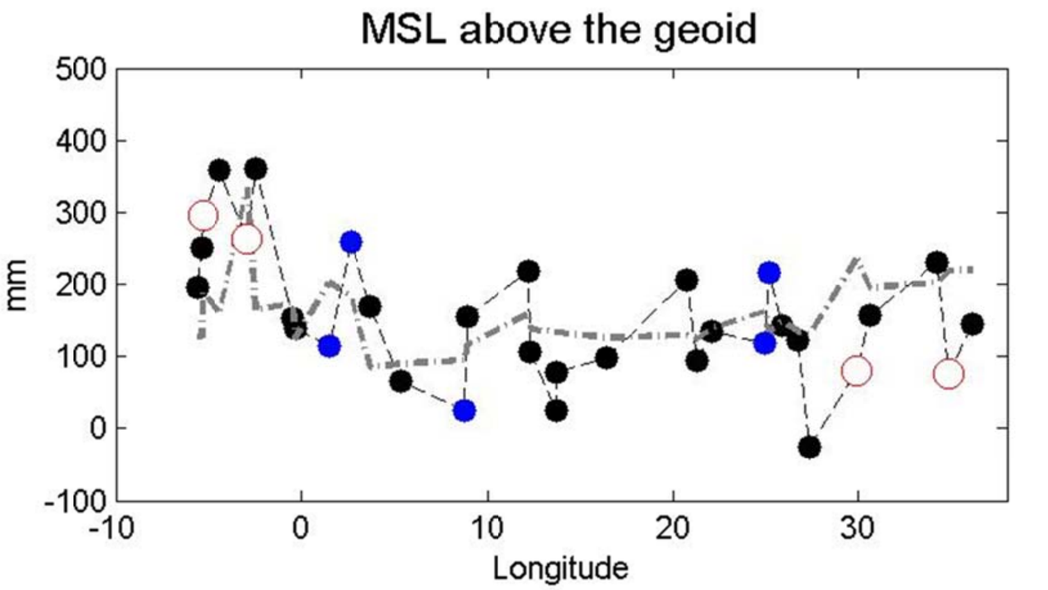


Figure 6

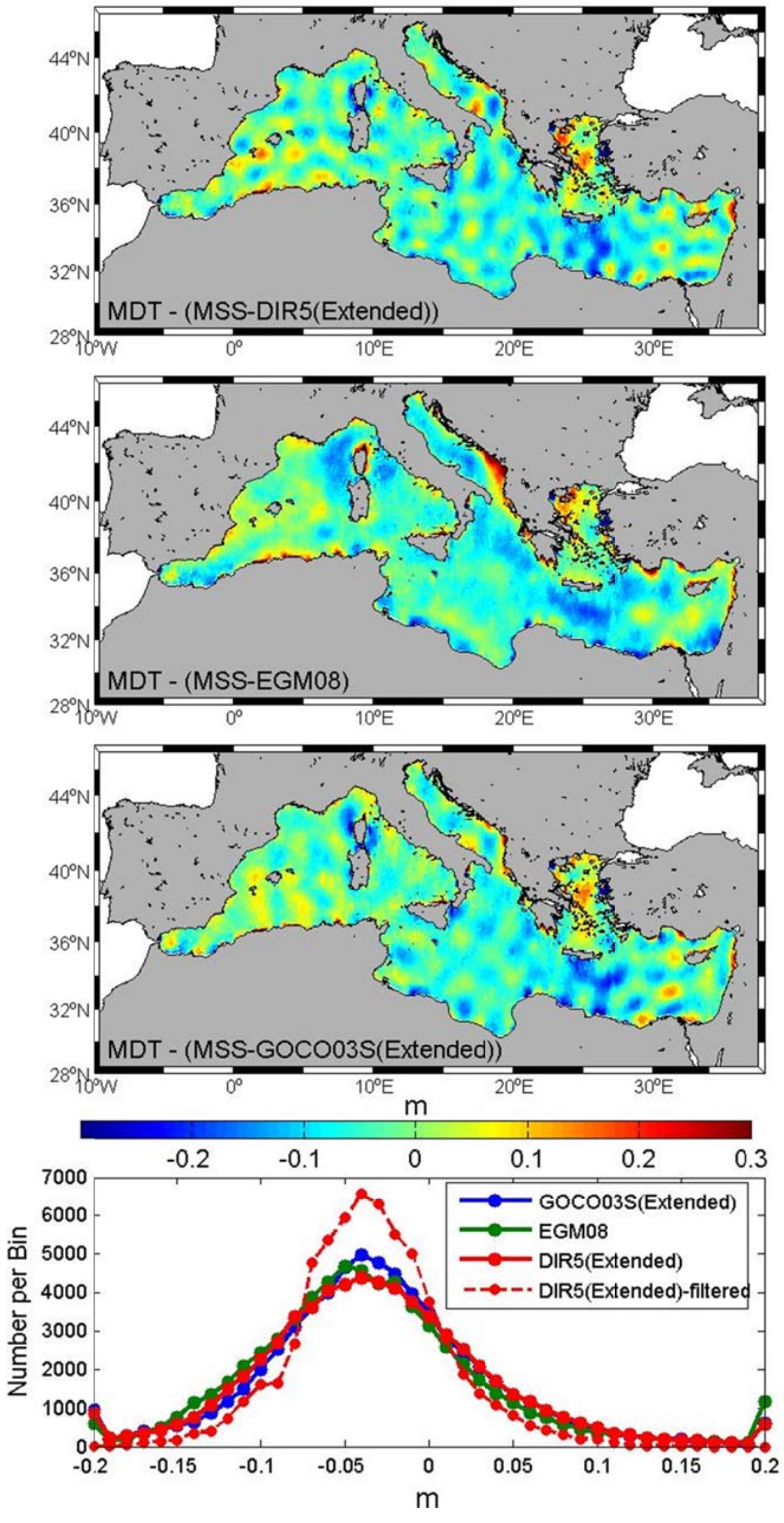

MDT - (MSS-DIR5(Extended))
MDT - (MSS-EGM08)
MDT - (MSS-GOCO03S(Extended))
44ºN
40ºN
36ºN
32ºN
28ºN
10ºW
0º
10ºE
20ºE
30ºE
m
-0.2
-0.1
0
0.1
0.2
0.3
Number per Bin
GOCO03S(Extended)
EGM08
DIR5(Extended)
DIR5(Extended)-filtered
0
1000
2000
3000
4000
5000
6000
7000
-0.2
-0.15
-0.1
-0.05
0
0.05
0.1
0.15
0.2
m

Figure 7

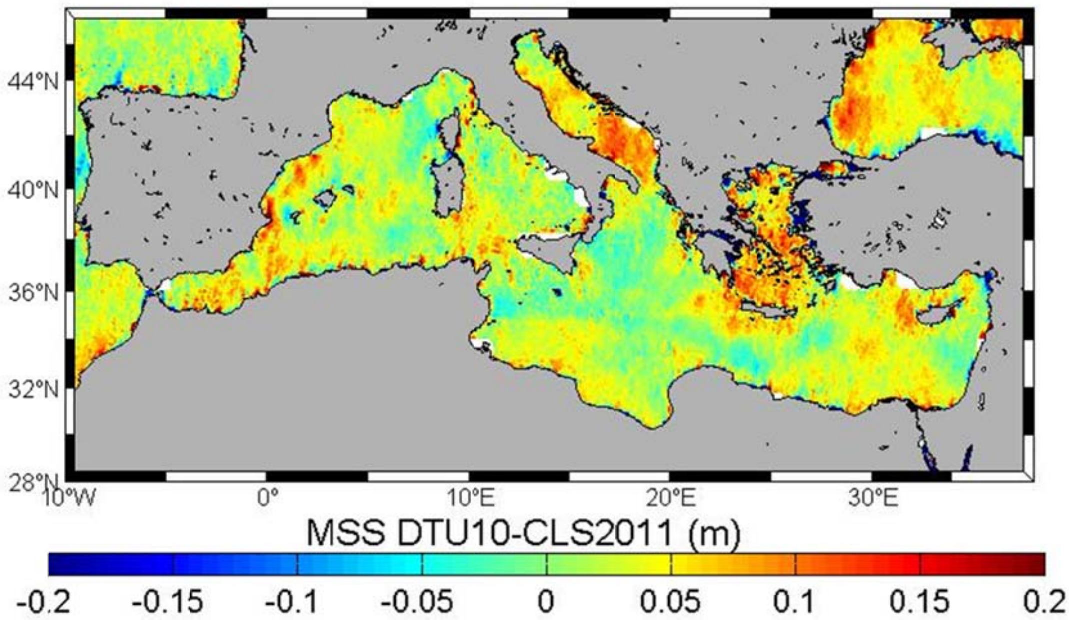

44°N
40°N
36°N
32°N
28°N
10°W
0°
10°E
20°E
30°E
MSS DTU10-CLS2011 (m)
-0.2
-0.15
-0.1
-0.05
0
0.05
0.1
0.15
0.2

Figure 8

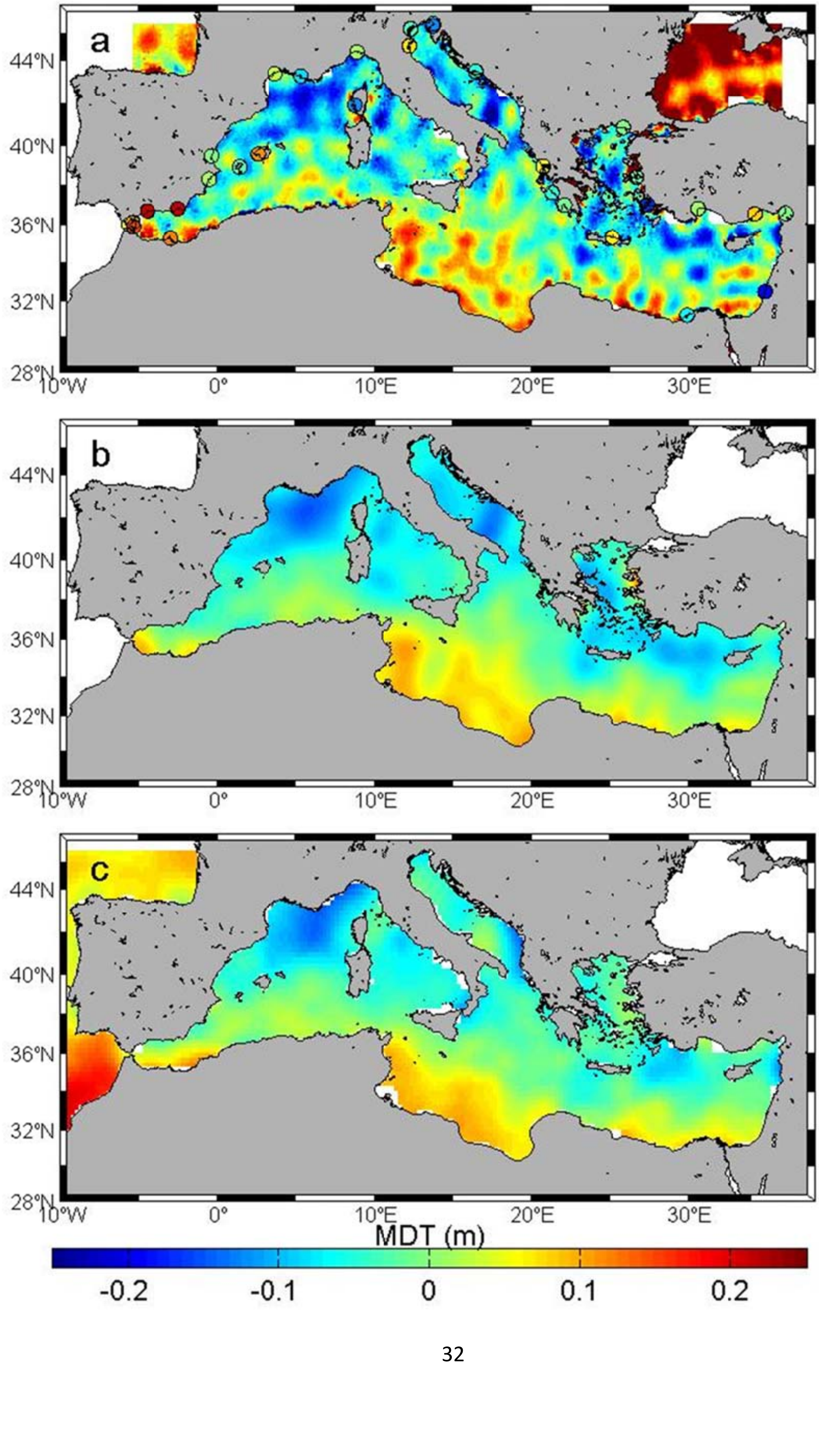

a
b
c
44°N
40°N
36°N
32°N
28°N
10°W
0°
10°E
20°E
30°E
MDT (m)
-0.2
-0.1
0
0.1
0.2

Figure 9 on previous page

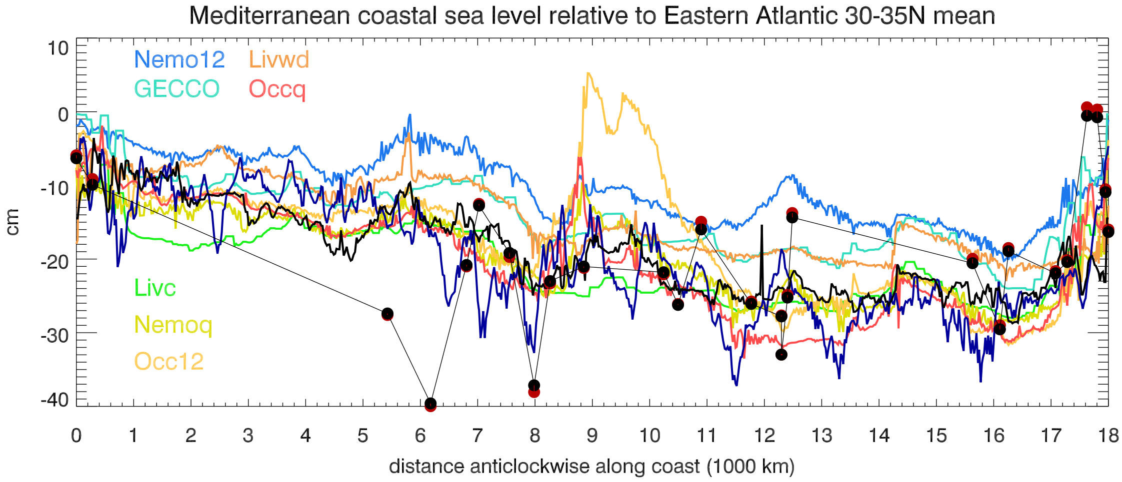


Figure 10